# The Development of NASA's Fault Management Handbook

**Cornelius J. Dennehy,* Lorraine M. Fesq****

**NASA Goddard Space Flight Center, Greenbelt, MD, 20771 USA*
*(e-mail: Cornelius.J.Dennehy@nasa.gov)*
***Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA*
*(e-mail: Lorraine.M.Fesq@jpl.nasa.gov)*

**Abstract:** Fault management (FM) is a maturing discipline; currently there is no unifying description or set of guidelines for this field. Disciplines related to FM such as Reliability and Hazard Analysis do have formal methodology documents, and in some cases, NASA Procedural Requirements to guide development of the work products. However, none fully addresses the needs of FM. FM is a key factor to increase safety, reliability, availability, and performance in systems, and requires the rigor of other safety-critical processes in order for significant improvements to be made. Without this rigor, improvements to safety and reliability will be limited.

A number of approaches to FM have been tried, and while many of these have been locally successful, they are inconsistent with each other and often deal with FM issues in a fragmented way. Currently it is difficult to assess the appropriateness of the architecture selected, the quality of the processes used and the development of interfaces, which can lead to designs that are complex and/or difficult to verify and validate. All of these approaches have difficulty addressing questions of completeness and effectiveness.

NASA is developing a FM Handbook to establish guidelines and to provide recommendations for defining, developing, analyzing, evaluating, testing, and operating FM systems. It establishes a process for developing FM throughout the lifecycle of a mission and provides a basis for moving the field toward a formal and consistent FM methodology to be applied on future programs. This paper describes the motivation for, the development of, and the future plans for the NASA FM Handbook.

*Keywords:* Fault management, fault tolerant control, safety critical systems, fault detection-isolation-response

## 1. INTRODUCTION

In 2008, the NASA Science Mission Directorate (SMD), Planetary Science Division, commissioned the first NASA FM Workshop [Fesq 2009] in response to a number of technical and programmatic issues surrounding FM experiences on numerous missions. The workshop was held in April 2008 in New Orleans, Louisiana. Although the workshop was to address a pattern of problems occurring across several planetary missions, the participants concluded that the challenges of adequate FM are present to a degree in all space missions. A primary recommendation from the workshop was the development of an FM Handbook that would benefit not only planetary missions but also all NASA missions. The NASA Chief Engineer and the NASA Constellation Program Chief Architect endorsed the development of an FM Handbook.

In 2010, the NASA Science Mission Directorate's Discovery and New Frontiers Program Office and the Office of the Chief Engineer's NASA Engineering & Safety Center (NESC) co-sponsored the development of the Handbook as an initial step to coalesce the FM field. As a result of this sponsorship, the initial focus addresses FM required for science missions. It is recognized that FM is relevant to all NASA missions, and that ultimately the Handbook should address the needs of the Agency. In preparation for this broadened scope, the authors have strived to develop an outline that identifies FM-related needs and goals for all Directorates, with the intent that the content for the Aeronautics Research Mission Directorate and the Human Exploration and Operations Mission Directorate will be completed in a future revision of the Handbook.

## 2. THE SCOPE OF FAULT MANAGEMENT

FM is an engineering activity; it is the part of systems engineering (SE) that addresses the off-nominal behavior of a system, as well as a subsystem that has to be designed, developed, integrated, tested and operated. FM encompasses functions that enable an operational system to prevent, detect, isolate, diagnose, and respond to anomalous and failed conditions interfering with intended operations. From a methodological perspective, FM includes processes to analyze, specify, design, verify, and validate these functions. From a technological perspective, FM includes the hardware and control elements, often embodied in software and procedures, of an operational system by which the management of faults and anomalous situations is realized. It includes a situation awareness capability such as

caution/warning functions to notify operators and crew of anomalous conditions, hazards, and automated responses. The primary goal of FM is the preservation of system assets, including crew, and of intended system functionality (via design or active control) in the presence of failures.

FM demands a system-level perspective, as it is not solely a localized concern. A system's design is not complete until potential failures are addressed, and comprehensive FM relies on the cooperative design and operation of separately deployed system elements (e.g., in the space systems domain: flight, ground, and operations deployments) to achieve overall reliability, availability, and safety objectives. Like all other system elements, FM is constrained by programmatic and operational resources. Thus, FM practitioners are challenged to identify, evaluate, and balance risks to these objectives against the cost of designing, developing, validating, deploying, and operating additional FM functionality.

FM as a discipline is still in the formative stage, as reflected by the different approaches used in many organizations, and by the ongoing activities to gain community consensus on the nomenclature. In fact, the term "fault management" is in itself something of a misnomer—the discipline of FM is concerned with failures in general and not just faults, which are failure causes rooted within the system. However, present use of the term "fault management" is synergistic with usage in the field of network management, where the International Organization for Standardization [ISO] defines FM as "the set of functions that detect, isolate, and correct malfunctions…." Likewise, the above-stated goal of FM (i.e., preservation of system assets and intended system functionality in the presence of failures) is consistent with the ISO-stated goal of having "a dependable/reliable system in the context of faults."

FM is crucial to the successful design, development, and operation of all critical systems (e.g., communications networks, transportation systems, and power generation/distribution grids). However, the architectures, processes, and technologies driving FM designs are sensitive to the needs and nature of the development organization, the risk posture, the type of system under development, and the targeted operating domain. Within NASA, FM is crucial to the development of crewed and robotic systems, in the development of flight controls and maintenance of aircraft, and in the procurement, contractual oversight, and acceptance of commercial launch vehicles and orbital transportation services.

## 3. THE DEVELOPMENT OF THE FM COMMUNITY OF PRACTICE

To aid in the development of the FM Handbook, NASA created a FM Community of Practice. [Topousis] A community of practice (CoP) is a group of people "who share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis." [Wenger] By deepening their own knowledge, they are able to improve the performance of an organization as a whole. Communities have existed throughout history, through organizations such as guilds and professional societies like AIAA, ASME, and IEEE, but until recently they were not formally and strategically established within the aerospace industry. Communities of practice not only are an effective means for capturing, sharing, and using knowledge, but also provide a means for collaboration and innovation. They have become a more prevalent component of knowledge management strategies and many major organizations. [Lesser] Communities focus on connecting the workforce across organizations, projects, geographies, and functions, exactly what NASA was seeking. [APQC]

Due to the geographically distributed nature of NASA, communities required an online presence that would be open to all personnel behind the firewall. In addition, many of the core competencies have hundreds of practitioners so routine face-to-face or teleconference meetings were simply not feasible. The online sites would have to become the gathering point for these practitioners. See Figure 1 for a snapshot of the FM CoP home page.

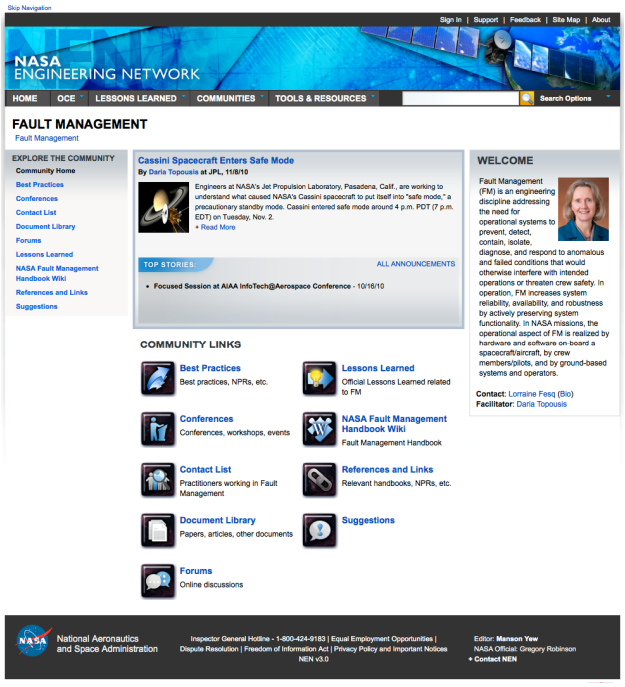


**Figure 1. NASA's FM Community of Practice Website**

CoPs can help NASA both capture undocumented engineering 'tribal knowledge' before it walks out the door and to overcome the inhibiting effects of insular professional development in rigidly stove-piped organizations. For FM, the benefits of creating a CoP included the specific objective of supporting the development and coalescing of this new and emerging engineering discipline that is still in the formative stage. FM is a non-traditional (relative to say the Structures discipline) engineering activity most often affiliated with the Systems Engineering discipline or the Software Engineering discipline. FM encompasses functions that enable an operational system to prevent, detect, isolate, diagnose, and respond to anomalous and failed conditions interfering with

intended operations. FM focuses on the off-nominal behavior of a system and it is a subsystem in its own right found on most NASA spacecraft. Similar to GN&C, Avionics, Structures, etc., FM is a subsystem that must be architected, designed, developed, integrated, tested and operated by NASA engineers, scientists and technicians. From a methodological perspective, FM includes processes to analyze, specify, design, verify, and validate these functions. From a technological perspective, FM includes the hardware and control elements, often embodied in sensors, software and procedures, of an operational system by which the capability is realized to autonomously respond to faults, anomalous conditions, and hazards. For example, a robust onboard FM system, tightly integrated with an autonomous GN&C system, is envisioned to be key element of any future NASA space platform operating beyond Low Earth Orbit (LEO).

Clearly FM engineering is an important part of the complex worlds of both human and robotic spaceflight at NASA but it is not easy to define, understand or effectively practice. Because FM is still in the formative stage, the engineering leadership at NASA decided to form a CoP focused on this emerging sub-discipline. Some of the primary objectives of this new CoP are the following:

- Provide an easy to use online forum for technical interaction and knowledge sharing between practitioners and managers across the FM community at NASA;
- Define, establish, and obtain a NASA-wide community consensus on a common set of FM nomenclature;
- Identify, document, and compare the different approaches for FM used across NASA, at its industry partners, and other organizations such as DoD;
- Identify, capture, and disseminate FM lessons learned from past NASA programs and projects;
- Provide a set of relevant probing questions to be posed at the specific FM system developmental milestones;
- Educate and inform space system architects and program/project stakeholders on FM, making them more aware and conversant in the issues and design options early in the development cycle;
- Identify, develop, and host tools/methods to properly scale ('right-size') FM systems relative to cost and risk;
- Identify, develop, and host analytical methods and techniques to help FM system designers balance/optimize automation versus human-in-the-loop (both in space and on the ground);
- Foster better communication and understanding of the challenges, options, and technologies of FM as applied to long duration spaceflight, especially with crewed vehicles.

The FM CoP recognized early on that although fault management is a maturing discipline, there currently is no unifying description or set of guidelines for this field. The current situation begs the question "Why is it acceptable to have a collection of *ad hoc*, uncoordinated approaches for FM, when it is not acceptable for any other safety-critical design process?" "This is what we have always done" is an insufficient answer, especially in the presence of program cost overruns, schedule slips, and in-flight failures traceable to a lack of disciplined approaches and systematic methods.

The CoP members understood that since FM is a key factor to increase safety, reliability, availability, and performance in systems, it should have the rigor of other safety-critical processes in order for significant improvements to be made. If the field does not mature by developing, documenting, and applying systematic methodologies for developing FM functionality, improvements to safety and reliability will be limited.

It is for all the above reasons and motivations that the FM CoP undertook the task of developing, for the first time, a NASA FM Handbook as a necessary step toward maturing the field. This handbook is the first tangible product to be delivered by the CoP. [Fesq 2011] FM is overdue to move from an 'art' to a 'science,' characterized by a known, agreed upon, and consistent methodology to structure FM and its relationship to other branches of engineering and design. The insights and concepts captured in this handbook provide a basis for moving the field toward a formal and consistent FM methodology to be applied on future programs.

## 4. THE CONTENTS OF THE FM HANDBOOK

The following bullets capture the outline of the FM Handbook, and provide insights into the contents of key sections.

- Foreword – Explains why NASA needs a FM Handbook and describes what this Handbook provides;
- Scope – Describes what is meant by FM, its relevance across the agency, and intended users of the Handbook;
- Definitions – An attempt to unify the terminology used in this field;
- Concepts and Guiding Principles – guiding principles grounding the field, describing FM functions, FM as part of SE, FM goals: asset and function preservation;
- Organization, Roles and Responsibilities – Suggested project organizational structure to support FM, interfaces and tasks;
- Process – Follows the NASA SE process but focuses on developing FM products including concept

design, requirements, architecture, analysis, V&V, operations and maintenance;

- Requirements Development – Defines FM requirements categories, identifies driving requirements and flow down;
- Design and Architecture – Explains the impacts of mission risk posture, goals and characteristics on FM priorities, provides insights into FM architectures, design features and approaches; highlights mission-specific considerations;
- Assessment and Analysis – will be supplied in later releases;
- Verification and Validation – Identifies FM V&V planning and preparation, how to perform FM V&V and to analyze results, selection and prioritization of FM test scenarios, ensuring sufficient capabilities in simulators, test-beds and ground support equipment to test for responses to anomalies and faults.

## 5. CONCLUSIONS AND FUTURE PLANS

The FM Handbook is a first step taken by NASA to coalesce the discipline. It offers guidelines and recommendations for defining, developing, analyzing, evaluating, testing, and operating the FM element of flight systems. The Handbook establishes a process for developing FM throughout the lifecycle of a mission and provides a basis for moving the field toward a formal and consistent FM methodology to be applied on future programs. The insights and concepts captured in the Handbook provide a basis for moving the field toward a formal and consistent FM methodology to be applied on future programs.

The Handbook in its current state is, admittedly, incomplete in two respects. First, a number of Sections were identified in the outline but have not yet been written due to lack of resources. Second, the Handbook captures concepts that are derived from robotic orbiters and deep space missions, which are only part of NASA's purview. FM is recognized as being an essential element of all NASA missions, and as such, the Handbook must also respond to the needs of human spaceflight, ground systems, mission systems and aeronautics, and must integrate seamlessly with functions performed by the NASA Office Safety and Mission Assurance. Activities currently are underway to bridge the gaps that exist between these communities, including activities to gain consensus on FM nomenclature.

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